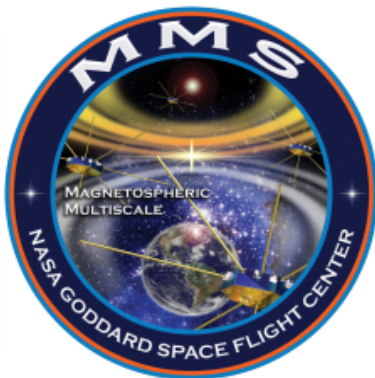
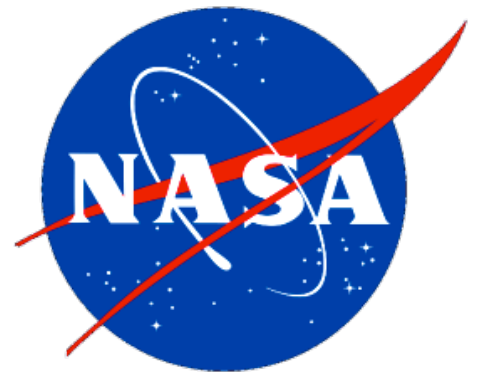


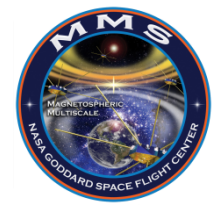
Precision Closed-Loop Orbital Maneuvering System Design and Performance For the Magnetospheric MultiScale (MMS) Formation

Dean Chai, Steve Queen, and Sam Placanica
Code 591 – Attitude Control Systems Engineering
NASA Goddard Space Flight Center

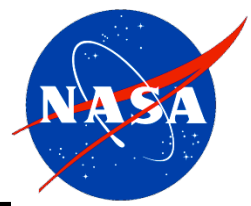


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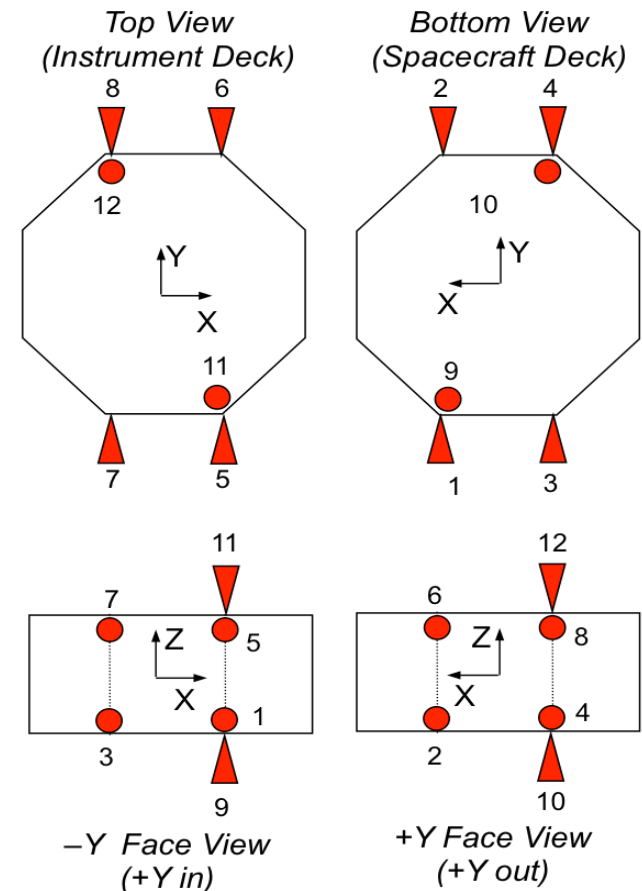


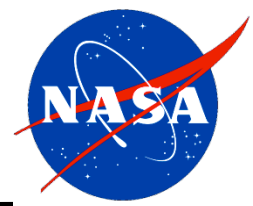
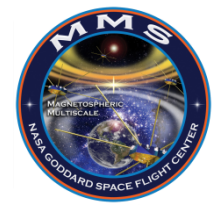


Observatory Overview



- Wet 1350 kg, Total deployed system MOI [2900; 2900; 5500] kg-m²
- On-Board attitude relies on DTU μ ASC with 4 Camera Head Units (CHUs)
- Delta-Velocity feedback uses ZIN Technologies Acceleration Measurement System [AMS] with 3 one-axis Honeywell QA-3000 accelerometers
- 8 radial Aerojet 17.8N and 4 axial AMPAC 4.4 N thrusters
- Spin-stabilized with spin-axis few degrees off of Ecliptic norm
 - 2x2 deg science box, pointing control requirement is 0.2 deg
 - 3.1 RPM nominal spin rate
 - Minimize transverse rate (nutation) though there is not a hard requirement





Derived Formation Maneuver Requirements

Driving Requirements

- Establish stable tetrahedron formation inside the science Region of Interest (ROI)

“A four-spacecraft tetrahedron formation shall be achieved with a quality factor $Q(t)$ greater than or equal to 0.7 for 80% of the time in the Control Region of Interest, excluding orbits with maneuvers, as averaged by phase (1A, 1B, and 2B).”

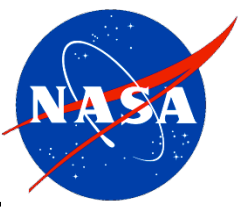
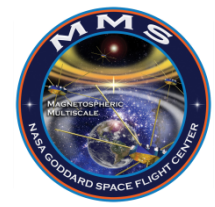
“During science operations (phases 1a, 1b, 2b), eighty (80) percent of the elapsed times between subsequent pairs of Formation and Attitude Maintenance... maneuvers shall be no shorter than fourteen (14) days, the remaining twenty (20) percent shall be no shorter than five (5) days.”

Derived Formation Maneuver Requirements

- Employed Monte Carlo Simulation
Techniques to establish 1) an absolute accuracy floor and 2) direction requirement especially for the very small maneuvers
- Actual performance is better though maneuver magnitude and direction are not something the team specifically reconstruct/assess

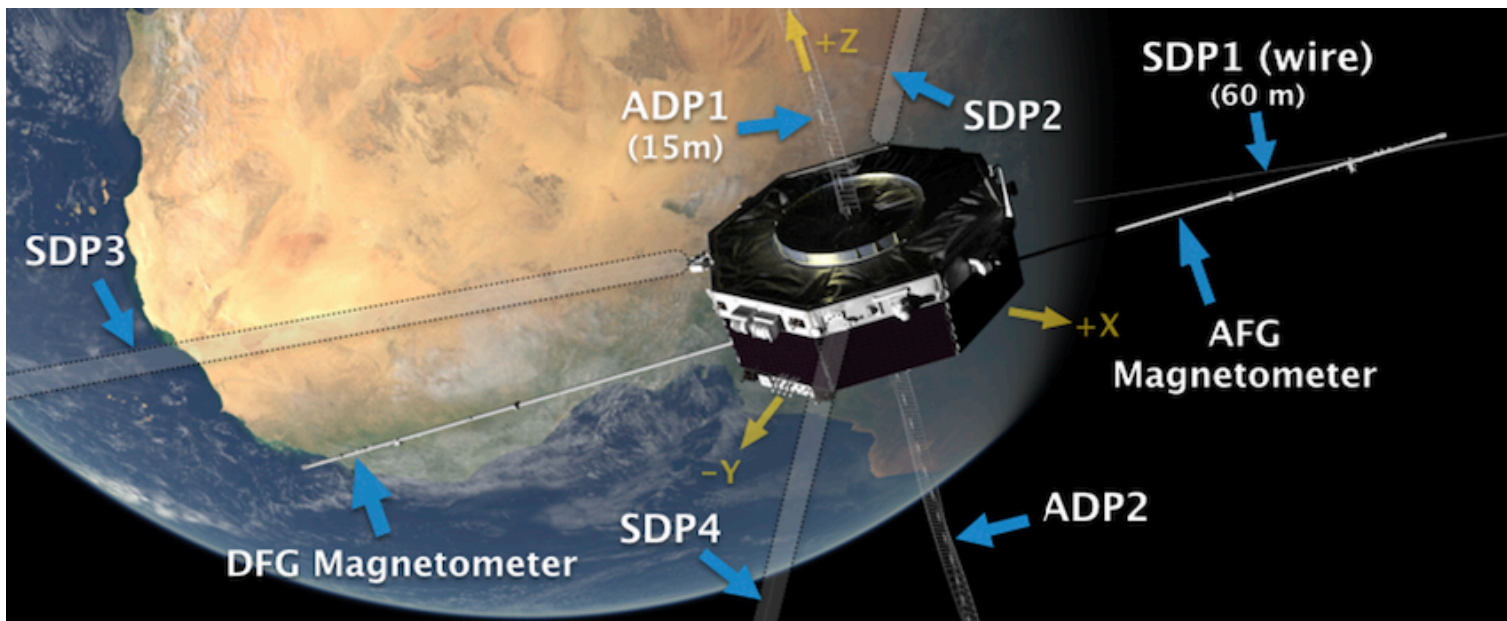
Maneuver Size [m/sec]	Error Allocation (3σ)	
	Magnitude	Direction*
0.00 – 0.10	< 5 mm/sec	40.0° -> 5.0°
0.10 – 0.50	< 5 mm/sec	5.0° -> 1.5°
> 0.50	< 1%	< 1.5°

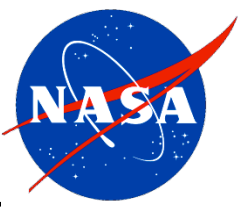
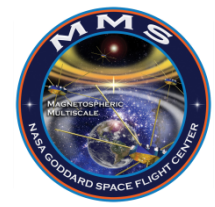
* ‘->’ denotes linearly decrease with maneuver size



Maneuver Safety Constraints

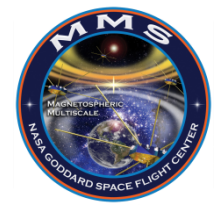
Safety Constraints	Limits
SDP In-plane Deflection	$< 14.0^\circ$
SDP Out-of-plane Deflection	$< 7.00^\circ$
SDP Tension at Retraction Point of Interest	$> 0.51 \text{ N}$
SDP and Magnetometer Boom Separation Distance	$> 1.00 \text{ m}$
ADP Root Bending Moment	$< 14.3 \text{ N-m}$



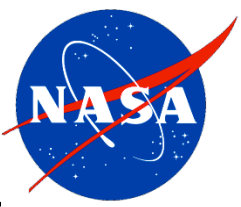


Acceleration Measurement System (AMS)

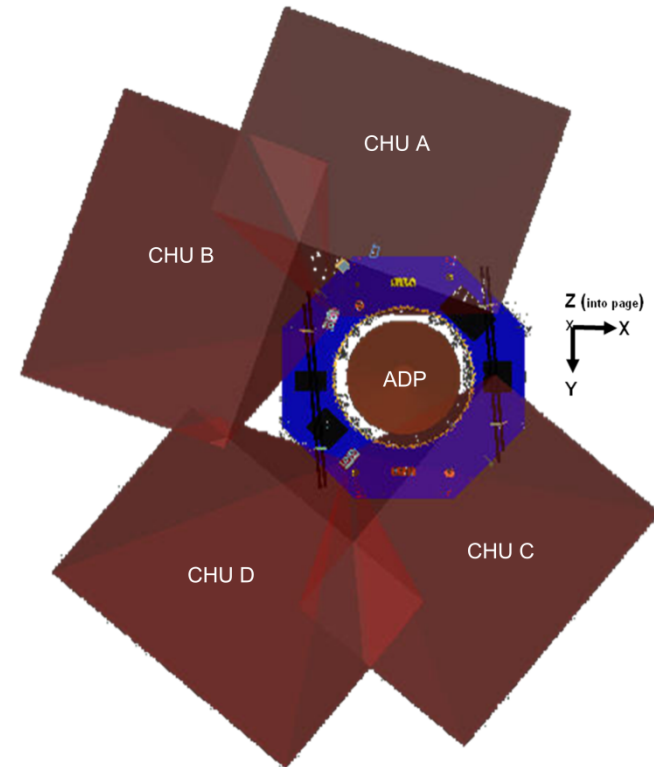
- ZIN Technologies, Inc (Cleveland, Ohio)
- It provides three-axis acceleration measurements (Honeywell QA 3000) as well as integrated delta-velocity during orbit adjustments
- Internally sampled at 100 kHz
- Embedded processor down samples and filters measured acceleration. Effective bandwidth of 250 Hz
- Resolution $<1 \mu\text{g}$ in high resolution mode
- Bias stability $<1 \mu\text{g}$ over a 12-hour period
- Onboard control system provides AMS estimated spin-rate and AMS bias before each closed-loop maneuver

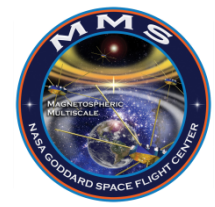


Attitude Determination with DTU Star Trackers

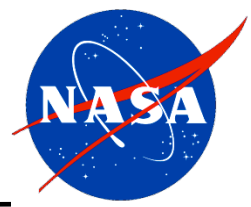


- Danish Technical University (DTU) μ ASC with 4 CHUs
- Advertised accuracy 60/60/200 arcsec
- Full performance level at up to 4 RPM spin-rate
- Raw quaternion measurements from all four CHUs are combined onboard with a Multiplicative Extended Kalman Filter (MEKF)
- Digital Sun Sensor measurement is not used in the filter due to lack of accuracy. It is only part of Sun Acquisition Mode

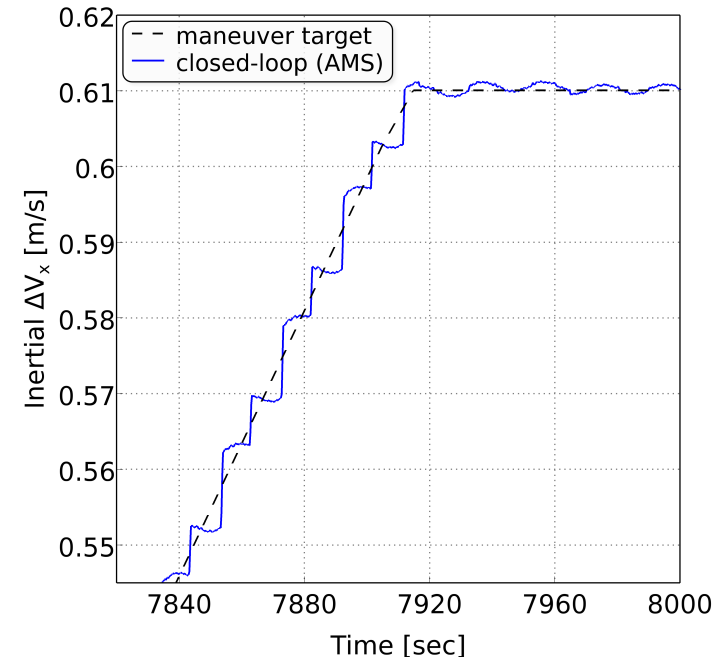




Orbit (Delta-V) Controller

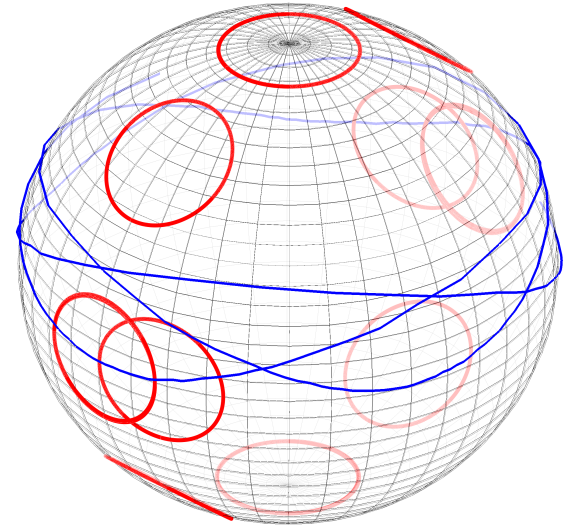


- 6-DOF Controller
- Separate logic for velocity control and momentum control
- Velocity control tracks an inertial Delta-V profile designed by Flight Dynamics
 - Radial control frequency is governed by spin-rate, 0.10 Hz
 - Axial control frequency is 0.2 Hz
- Momentum control holds the current attitude in order to minimize SDP boom excitation
 - Control frequency, 0.33 Hz, is chosen to avoid ADP boom excitation
- For the most part, the two control logics and their associated thruster commands are interleaved. Whenever the same thrusters are selected, velocity control is given the higher priority. Attitude adjustment can wait till the Delta-H portion of the maneuver sequence.
- Off-pulsing of axial thrusters is an exception to the above rule. This feature is implemented relatively late in the design phase, one of the lessons from Monte Carlo methods, in order to handle maneuver corner cases where the Delta-V targets are predominantly axial and that radial thrusters are precluded for control due to geometry.

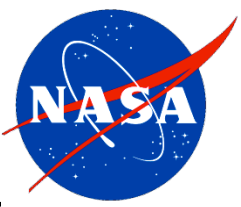
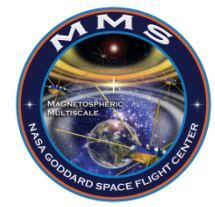


Momentum (Delta-H) Controller

- A non-linear, Lyapunov controller using Path-Weighted methodology, an extension of Reynolds-Creamer's work for RHESSI. The Lyapunov Function contains three quadratic components:
 - Pointing error term -> Align angular momentum vector toward the inertial spin-axis target.
 - Nutation term -> Minimize transverse rate about non-major-principal spin-axis direction.
 - Spin-rate "energy" error -> Drive spin-rate to the target spin-rate.
- At every Delta-H control cycle, the controller cycles through all 14 thruster torque pairs searching to rate error within the torque authority circles prescribed by an efficiency angle/radius then command the most efficient pair of thrusters.

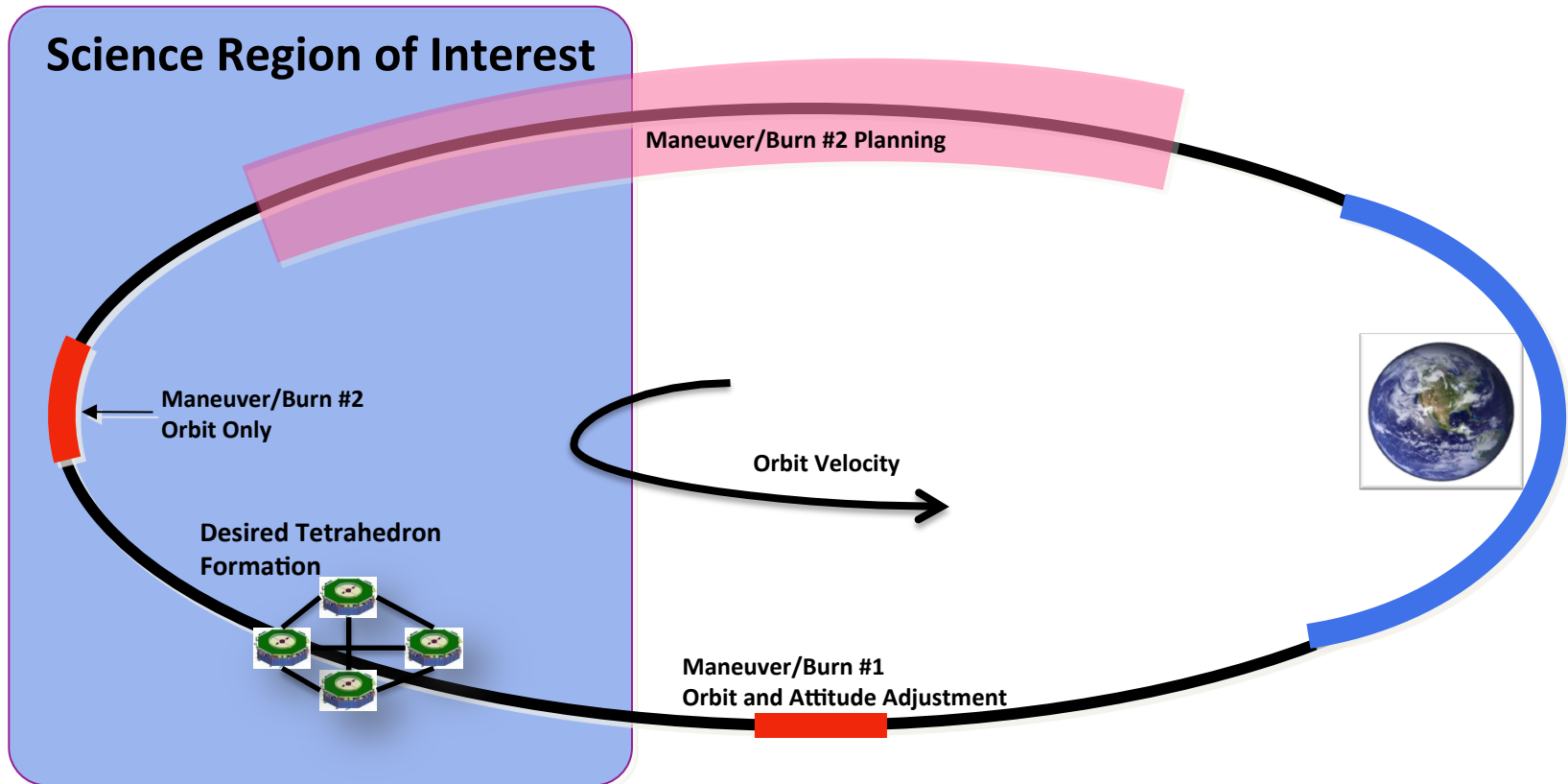


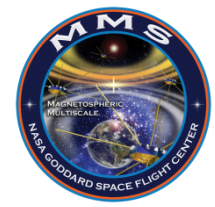
Blue line is the path of rate error in body sphere. Thruster Actuation when blue line enters the torque authority circles (red)



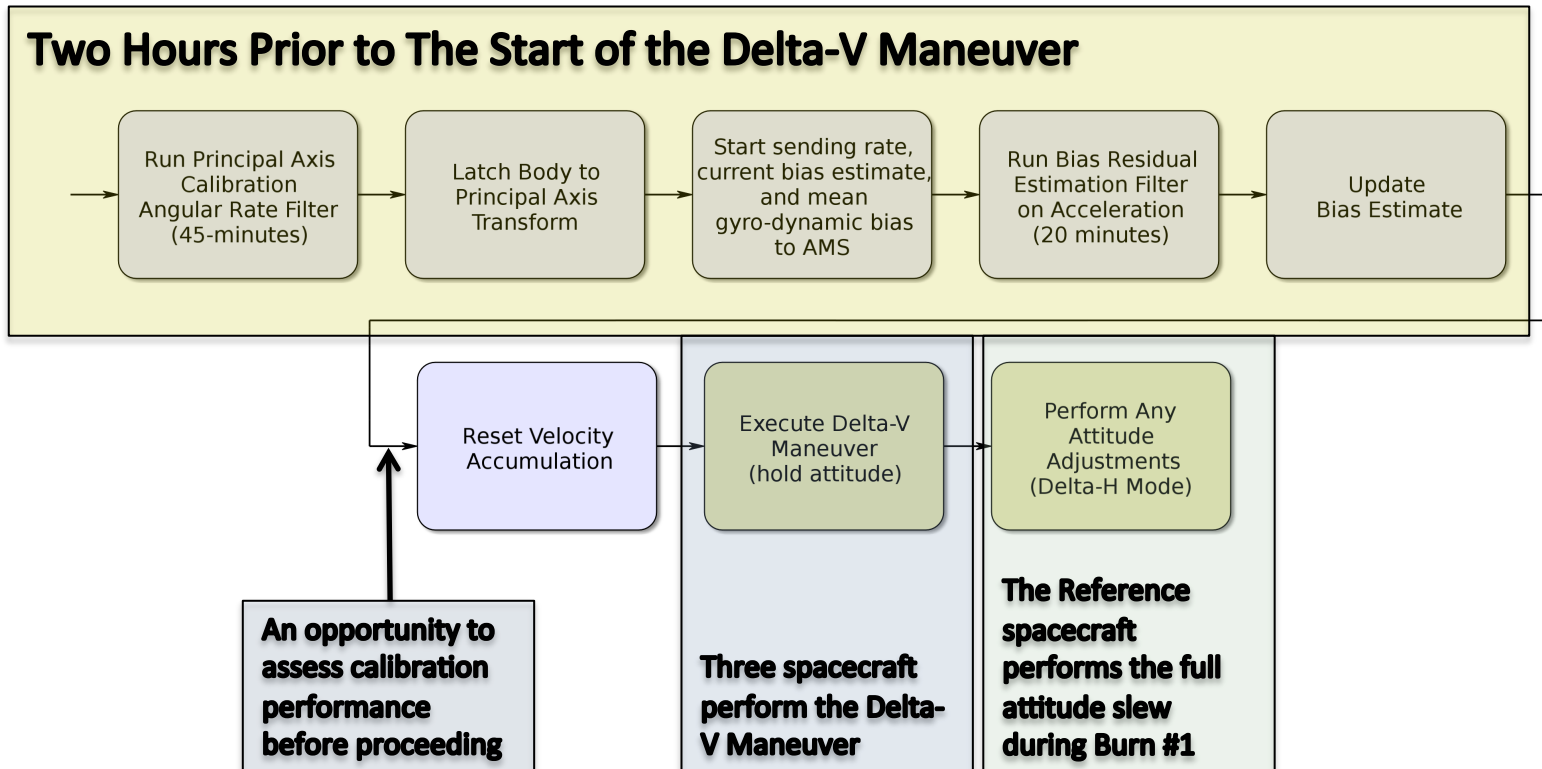
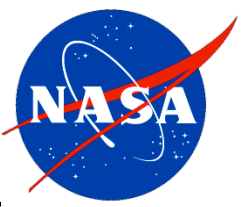
Formation-Class Maneuvers

- Initialization, Maintenance, Resize, or, in general, all maneuver types where high accuracy (1%) is needed and thus closed-loop Delta-V control is required.



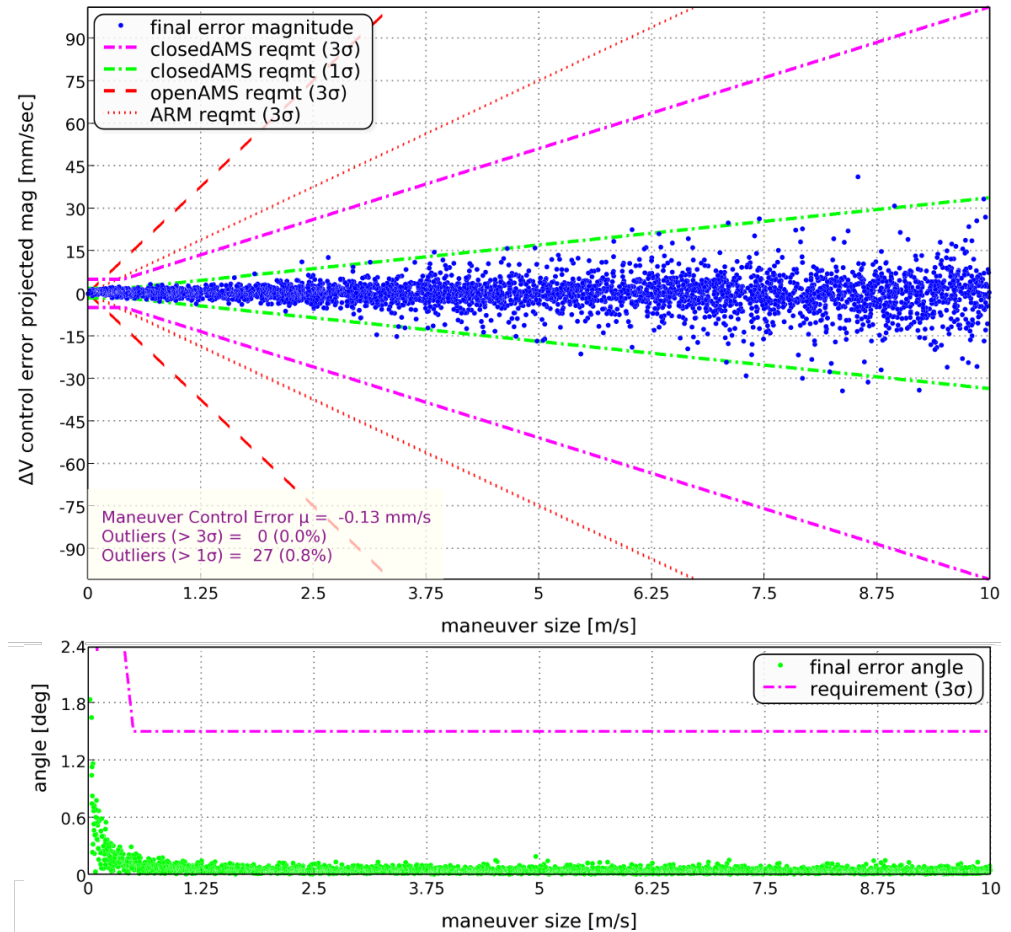


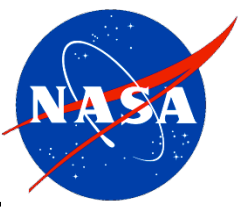
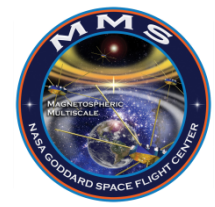
Formation Maneuver Sequence



System Robustness via Monte Carlo Method

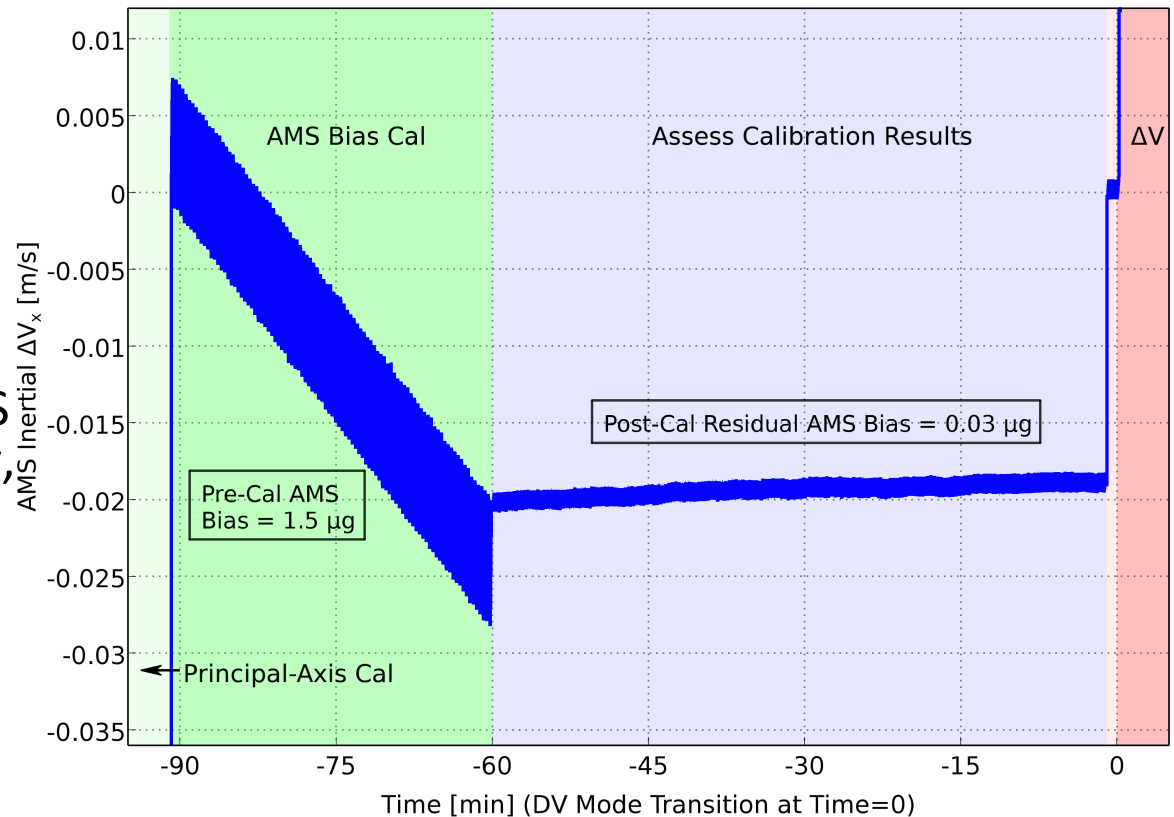
- Monte Carlo Method is used to demonstrate system robustness and performance in the presence of plant uncertainties.
- Based on the statistical method outlined by Hanson and Beard, a 99% confidence criteria was selected that permits zero failures for a sample size of 3410 runs.
- Using NASA Goddard's Freespace Simulation Environment and its parallel processing capabilities, the method varies over 250 model parameter resulting in hundreds of thousands of time-domains simulations of maneuvers at full model fidelity.
- On several occasions, Monte Carlo method exposed unexpected control and multi-body interactions. This made Monte Carlo Method an effective tool for fine tuning controller parameters during design phase.

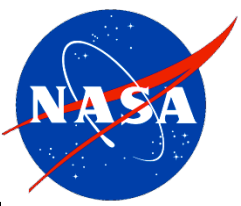
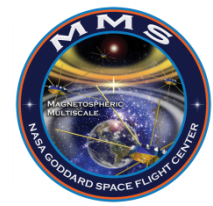




On-Orbit Calibration Performance

- On-Orbit principal axis calibration and AMS bias calibrations effectively removed principal axis uncertainty, rate estimate uncertainty, and AMS bias uncertainty.
- They, along with AMS superior bias stability, provided the knowledge performance needed for high precision formation control.



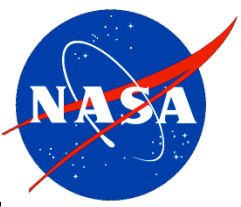
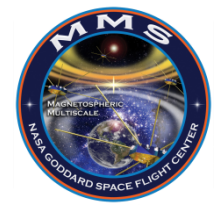


Closed-Loop Maneuver Performance

- The GSFC-developed GPS-Enhanced Onboard Navigation System (GEONS) software provided the best maneuver assessment metric: SMA Δ -error
- The quoted errors are 'Total Error' including maneuver execution, navigation, planning.
- Based on this relatively small sample size of 20 cases, we can state with a 90% confidence that the true standard deviation lies in the range of 0.401–0.692%

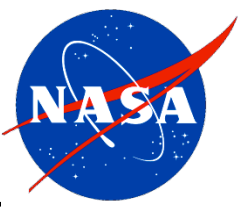
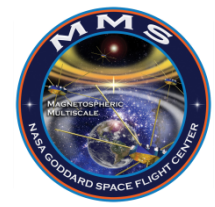
Table 3. On-Orbit Formation Maneuver Performance

Maneuver (DOY)	Obs ID	Final Target Magnitude mm/s	GEONS Solution Semi-major Axis Δ -error	Final Servo-Error		AMS Bias Estimate (μ g)		
				mm/s	% target	X	Y	Z
GS ¹ -095 (166,167)	1	118.6	-1.14%	1.5	1.25%	114.7	78.9	49.6
	2	18.3	-0.57%	1.0	5.73%	94.3	93.9	47.3
	3	46.9	-0.73%	1.1	2.27%	75.2	92.5	140.1
	4	77.0	0.55%	1.1	1.44%	108.3	96.1	125.1
FI ² -116 (188)	1	0	—	—	—	115.3	77.4	49.7
	2	4077.5	-0.79%	1.0	0.03%	95.0	94.0	47.5
	3	9175.6	-0.26%	0.2	0.00%	76.9	94.3	140.9
	4	4452.1	-0.26%	1.2	0.03%	107.2	93.9	125.4
FI-119 (190)	1	0	—	—	—	—	—	—
	2	3511.6	-0.61%	0.8	0.02%	93.7	94.0	47.6
	3	4149.7	-0.18%	1.3	0.03%	76.9	94.7	140.8
	4	6068.7	-0.27%	1.3	0.02%	106.9	95.5	125.3
FM ³ -139 (211)	1	1086.4	-0.70%	0.4	0.04%	114.3	77.1	49.4
	2	0	—	—	—	—	—	—
	3	0	—	—	—	—	—	—
	4	1714.3	0.08%	1.0	0.06%	107.1	98.4	125.8
FM-140 (211)	1	2688.5	0.41%	1.5	0.06%	114.5	77.3	49.2
	2	0	—	—	—	—	—	—
	3	0	—	—	—	—	—	—
	4	1259.2	0.27%	0.9	0.07%	106.8	98.6	125.8
FM-172 (243,244)	1	1369.6	0.04%	0.8	0.06%	114.6	76.8	48.8
	2	1008.1	-0.31%	1.5	0.15%	95.9	94.6	47.0
	3	2537.0	0.5%	1.2	0.05%	76.5	94.6	141.1
	4	0	—	—	—	—	—	—
FM-173 (244)	1	1406.9	-0.27%	0.8	0.06%	115.1	76.6	48.5
	2	748.8	-0.30%	0.4	0.05%	95.5	94.7	47.1
	3	1440.0	0.34%	1.1	0.08%	76.4	94.1	141.1
	4	0	—	—	—	—	—	—



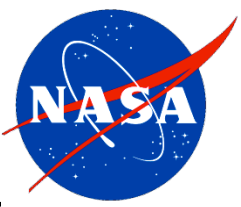
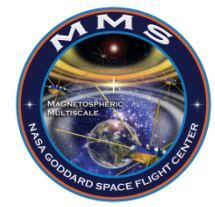
Conclusions

- The MMS control system, including hardware, formation controllers, and the entire maneuver sequence design, has demonstrated its effectiveness in carrying out high precision orbit maneuvers.
- The smallest formation tetrahedron to-date is 25 km, and they are stable well beyond our two-week design goal.
- Unlike traditional orbit maneuvers, MMS formation maneuvers can achieve sub-1% accuracy without any “fudge factor” involved in maneuver planning or reconstruction, which simplifies ground processing.
- MMS paved the way for the next generation of Formation Flying missions to come.



Other MMS ACS Papers

- Queen, S., Chai, D., and Placanica, S. “Orbital Maneuvering System Design and Performance for the Magnetospheric Multiscale Formation.” “AAS/AIAA Astrodynamics Specialist Conference,” Vail, CO, August 2015. AAS 15-815.
- Queen, S., Shah, N., Benegalrao, S., and Blackman, K. “Generalized Momentum Control of the Spin-Stabilized Magnetospheric Multiscale Formation.” “AAS/AIAA Astrodynamics Specialist Conference,” Vail, CO, August 2015. AAS 15-816.
- Queen, S. and Benegalrao, S. “A Kalman Filter for Mass Property and Thrust Identification of the Spin-Stabilized Magnetospheric Multiscale Formation.” “25th International Symposium on Space Flight Dynamics ISSFD,” Munich, Germany, October 2015.
- Raymond, J. C., Sedlack, J. E., and Vint, B. “Attitude Ground System for the Magnetospheric MultiScale Mission.” “25th International Symposium on Spaceflight Dynamics,” Munich, Germany, October 2015.



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